

A French Pre-WW II Attempt at Air-Warning Radar: Pierre David's "Electromagnetic Barrier"

Yves Blanchard

Historian, Consulting Engineer
Retired from Thales, Paris, France
E-mail: yvfrancb@club-internet.fr

Abstract

Pierre David, a French pioneer of the 1920s in the VHF domain, is best known for his early work on air defense and detection of aircraft. His approach, which he called DEM (electromagnetic detection), was quite similar to the "beating method." There was experience with this at the same time at the American Naval Research Laboratory (NRL), and this is recognized to have initiated the radar concept in the US. Other developments in Great Britain and more especially in Japan are also discussed. However, David was certainly the person who went the furthest in field applications to develop a French operational system that could meet the pressing threat of German Nazi aviation. The results of the full-scale experiments of his "Electromagnetic Barriers" are described from test reports of the French Air Force, unpublished to this day. A "Compagnie de Guet Electromagnétique" (Electromagnetic Warning Company) was established to build a Chain Home "à la Française" along the German border. The outbreak of the war did not allow its deployment, apart from a limited facility in the Marseille region. However, the principles that David had established to find an efficient solution for a true three-dimensional localization (leading to the "Maille en Z" method) prefigured the modern approach of generalized multi-static sensor systems, which is popularized today under the MIMO (multi-input multi-output) concept.

1. Introduction

“Radio Detection Finding” (RDF), “Dezimeter Telegraphie” (DeTe) or FunkMessOrtungsGerät (FuMO), “Radio Detector Telemetro” (RDT), “радиоуловитель самолётов” (RUS, Radio Ulovitel Samaliotov): This extended list of code names used throughout the world before the adoption of the universal acronym RADAR (radio detection and ranging) is an

eloquent illustration of the great variety of technical developments undertaken in this field between the wars, in all industrialized countries [1, 2]. As for France, it is known that two distinct approaches were explored very early [3, 4]. The first one resulted from advanced studies of the CSF company on the magnetron: the history of the first centimetric radar, which equipped the liner *Normandy* in 1935 [5], was recently recalled in various papers [6, 7]. Here, we will look at the second approach, initiated around 1925 by the French engineer Pierre David. This has to be placed in the context of the period, and compared to other implementations in the USA, Great Britain, or Japan. These systems, typically working on a bistatic scheme, were generally limited to an alerting function. However, David tried to give them a real capability for three-dimensional localization, to be inserted in a global project of air defense. The outbreak of WW II did not allow carrying out the full implementation, but the interest given today to multi-static systems sheds a new light on the premonitory aspects of David's "Electromagnetic Barriers."



Figure 1. General Ferrié (about 1930).

2. Pierre David, Disciple of General Ferrié, and French Pioneer of Electromagnetic Detection

Pierre David (1897-1987), graduated in 1920 from the Ecole Polytechnique and also received the Doctor of Science. Like most pioneers of the French radio industry, he began his career in the famous Laboratoire Central de TSF [Central Laboratory of Wireless-Telegraphy]. This was created after WW I by General Gustave Ferrié (1868-1932) (Figure 1) to avoid the dispersion of his team of the Radiotélégraphie Militaire [Military Radiotelegraphy], and to save the high technical potential reached during wartime. At that time, Ferrié was recognized throughout the world as one of the most important initiators of radio technology. He had acquired a dominant position in the history of this field, for instance, as a founding member of URSI, and as first President of the French URSI Committee. His new laboratory was given a mixed status, involving both civilian and military staff, under the joint supervision of the War and PTT ministries. Its mission was to “combine scientific research with practical experiments and implementation of prototype devices.” In 1931 it became the LNR, Laboratoire National de Radioélectricité [National Radioelectricity Laboratory].

David (Figure 2) was one of the four civil engineers who had served since 1920 in the first nucleus of the Ferrié team. With his colleague, Professor René Mesny, he engaged in his first research towards what they called the “very short waves.” Returning to the frequency range used by Hertz (while Marconi’s wireless telegraphy needed longer and longer waves, as long as 30 km by the end of WW I) was not just a matter of pure curiosity! They were looking to replace radio links that indiscriminately flooded the whole space with directive beams working from point to point, as in an optical connection. In 1923, René Mesny went right down to wavelengths of 1.2 m, using a symmetrical assembly of two classical triodes. With Pierre David, he organized a public demonstration of an experimental radio link at the Physics and Wireless Telegraphy Exhibition of Paris [8], showing good telephone communication on a 2 km phone link. The wavelength was still close to one meter, and the range was quite short, but the purpose was clear. Through slow but steady progress, these pioneers reached the borders of the *microwave* domain, opening the way to other unexpected applications that were still to come – such as radar.

It was in this field that David proved to be a real visionary. As soon as 1925, he was the first at the Laboratoire National de Radioélectricité to take interest in the problem of aircraft detection, at a time when the question was not yet of great priority.

During propagation tests on metric waves in June 1925, he observed that the reception was frequently

disturbed by electromagnetic noises coming from nearby combustion engines – cars or motorbikes on the ground – and also aircraft flying within a 500 m radius. Reporting this to General Ferrié, he proposed to test detection of planes by “listening” to the noises produced by the electric ignition of their engines. He probably ignored that such an idea had already been suggested by Major E. H. Armstrong of the US Signal Corps, when Armstrong served in 1918 as a radio expert in the American Expeditionary Force in France. As a matter of fact, Armstrong’s fame was actually based on his invention of the superheterodyne receiver. David was allowed to try a field experiment, which was made at Le Bourget airport on March 30, 1927, with the assistance of Prof. Mesny and Captain Nicol from the French Air Force. With a super-reactive receiver, it was found that some planes were detected at 3 km, but some others were not detected at all. It was then decided to continue the study in better conditions, with a directive antenna and a radio-goniometric receiver, on the Palivestre facility, near Toulon.

For reasons of aircraft availability, this second campaign was postponed until the spring of 1930. The measurements were performed by Messieurs David and Maginot from April 1 to 10, with a lot of various aircraft. Three types of antennas were used: an antenna of five horizontal wires, each 15 m long, horizontally fanned out at 4 m above the ground; an Adcock-type antenna with four vertical dipoles on a 10 m diameter cylinder, for direction finding (Figure 3); and occasionally, a square frame with sides of 7 m. In every test, the receiver was a super-reactive “universal E20,” tuned to wavelengths between 12 m and 25 m.



Figure 2. Pierre David (l) presenting Ferrié’s prize to M. H. Carpentier (r) in 1969.

The new results confirmed the 1927 results, with a slight improvement. All aircraft were listened to, at ranges that could likely be increased with a more-sensitive receiver. However, the source location remained quite imprecise, despite the use of the goniometer and various attempts to improve the location [9]. (It can be added that some infrared detection was also simultaneously performed, with even poorer results.)

The report concluded with the possibility of further improvements. However, even before the second test campaign, David had understood that these efforts would be useless. The countermeasure was too obvious, and already on the way: as these ignition noises confused the onboard radio links as well, engines were shielded more and more to suppress them. He concluded that, “the tests did not prove a sufficient military value, due to the easiness to stop any detection by shielding the magnetos,” and the study was abandoned.

However, the matter was not! As he felt his semi-failure was an incentive, David now focused his mind on this exclusive problem of aircraft detection. His decisive idea came out then, much richer than any previous idea, and it heralded all the further developments of “electromagnetic detection” in France. David suggested that even though new shielding could prevent any electrical radiation, it would still be possible, using his own words, “to force the planes to radiate,” in some way despite themselves “by taking them into the field of a beam of HF radio waves.” A short calculation proved that at metric wavelengths, any aircraft would reflect a sufficient part of the received energy to make an echo perceptible by a ground receiver [10].

This quotation deserves a moment of attention. Since Christian Hülsmeyer, it was the first expression of a clear

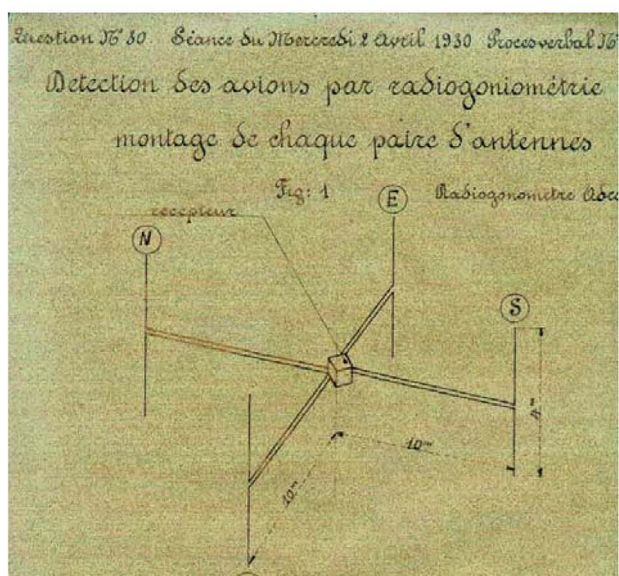


Figure 3a. The Palivestre trials (February 1930): the Adcock antenna [9].

“active-sensing” concept, as opposed to all the “passive systems,” either acoustical or optical, considered before. David revived Hülsmeyer’s idea, in which the radio transmission had no other purpose than to generate an echo: the idea that made radar a definitively new application of Hertzian radio waves.

David presented his suggestion to General Ferrié in a memorandum [11], which was sealed in a “*Soleau enveloppe*” (a French method used as a provisional proof of priority of invention, before it could be patented). This document was dated June 5, 1928, and was only reopened in May 1935. It must be seen as the true “birth certificate” of French radar.

Unfortunately, it seems that no copy of this historic memorandum has been preserved. However, we were lucky enough to find a good indication of its contents through a letter from General Challéat, Chief of the Artillery Service of Research, reporting a conversation held between David and Captain Lefranc at the end of 1928 [12]. David already suggested, if the Palivestre tests would be insufficient, to study a new device based on a different principle:

...it would give a plane detection through the perturbation it would bring to radio waves emitted by a ground station. This process would be sensitive enough to detect the waves emitted by any type of aircraft, which is an advantage on the current “listening” study.

Challéat was ready to undertake tests in this way, without waiting for the results of the current study.

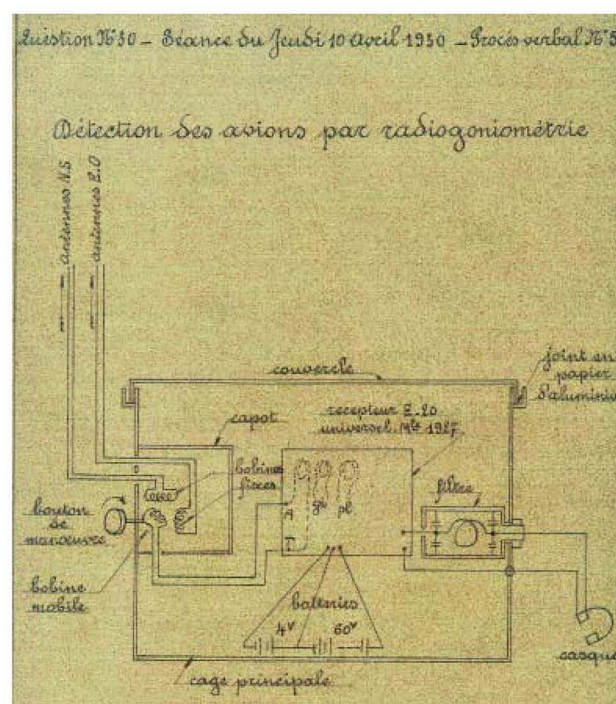


Figure 3b. The Palivestre trials (February 1930): the E20 goniometric receiver [9].

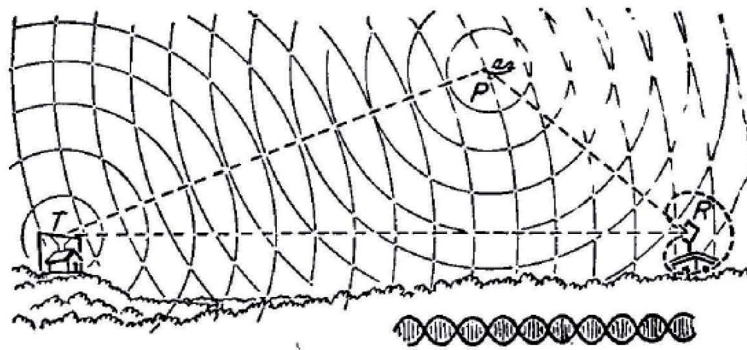


Figure 4. The Naval Research Laboratory beat method [13].

However, despite the urgency, nothing happened in the following years. The inventive process seems to have been slowed down by the lack of an operational need clearly expressed by the military staff, while things moved much faster elsewhere, and particularly in the United States.

3. A Welcome American Reference

An interesting parallel can be drawn with what arose during the same period at the US Naval Research Laboratory (NRL), where quite similar ideas had emerged from 1922 to 1930, at the initiative of two radio engineers, A. Hoyt Taylor and Leo C. Young.

Their story, which has been told by their younger colleague, Robert Page [13], begins in mid-September 1922, on a day where they tested a directive radio link across the Potomac River. Having obtained the correct tone for which they, they were suddenly surprised with an unexpected swell that nearly doubled its normal amplitude, followed by a quasi-extinction, the same process being reversed several times (Figure 4). The affair could have stopped there, and been forgotten as well. However, they noticed that this occurrence had coincided with the passage of a river steamer across their line of sight. As naval engineers, familiar with Navy problems, they immediately thought that this effect could be used to prevent enemy ships from penetrating harbors or fleet formations at night. Their letter to the Navy Bureau of Engineering, suggesting to use this as a “radio alarm”, was the first US proposal for the use of radio to detect moving objects in space. It was dated September 27, 1922.

However, nothing resulted until a second “accident,” which this time involved an airplane flying overhead. It was observed on June 24, 1930, by the same Leo C. Young and L. A. Hyland. It was then reported to A. G. Taylor, then head of the laboratory. It was clearly identified as a beating phenomenon between the direct signal and a second signal re-radiated from the intruder. Something new was also revealed: if it was not really surprising that a large ship reflected a detectable signal, it was much more unexpected with a small wooden plane!

This time, Taylor took time for further tests with different antennas and frequencies, before transmitting on November 5, 1930, a detailed 11-page report to the Bureau of Engineering. To establish his argument, one month later he organized a demonstration of this radio-detection method, which he called the “beat method.”

At about the same time, similar views were thus shared by the French Laboratoire National de Radioélectricité and the American Naval Research Laboratory. However, while David’s projects were stopped by his superiors in France, for the next three years, from 1931 to 1933, Taylor and Young would pursue their feasibility tests at the secret facility of Dahlgren. Using a 29 MHz, 500 W transmitter, and a receiver separated by about 5500 m across a small hilly area, they succeeded in detecting a small aircraft up to a distance of about 75 km. To finalize the question, a patent, entitled “System for Detecting Objects by Radio,” was filed on June 13, 1933 [14]. The affair was then transferred to the Army Signal Corps: at the Naval Research Laboratory, the time had come to give priority to the pulse-radar developments.

This research was conducted in a military secret context. However, the basic phenomenon that had initiated the work was fortuitously observed again in 1932 by civil engineers of the Bell Laboratories, and published in March 1933 in the *IRE Proceedings* [15]. This gave the opportunity of a new departure to Pierre David.

4. David’s Efforts to Achieve an Operational System (1934-1935)

This publication in the open literature encountered special attention in France. The paper suggested that the observed effect could be used to detect an aircraft “to unsuspected distances,” which was exactly the basis of the proposal registered by Pierre David in his memorandum of June 1928. However, while at that date he could benefit from a real advance of two years before the first observations of Young, he now found himself three years too late!

Moreover, the situation had become less favorable, in the meantime. Since the summer of 1931, the Laboratoire

National de Radioélectricité had been led by Prof. Camille Gutton, a former assistant of Ferrié at the Military Telegraphy during WW I, and then a world expert in ultra-short waves. Quite naturally, he favored those new frequencies in the projects of the laboratory, including the questions of detection – which was clearly premature (the idea would later be developed with success by his own son, Henri Gutton, at the CSF company [6]). This led Camille Gutton to a negative attitude towards David's efforts and, to say the least, to not encourage David. This was an attitude that only grew worse with time.

However, this time David held a key argument: from then on it became impossible to maintain that an electrical effect, which had been fortuitously observed by operators who were not looking for it, should be invisible to those who would seek it! The affair rose to the War Ministry through the CEEP, Comité d'Etudes et d'Expériences Physiques [Committee for Studies and Physical Experiments], in charge of steering military research. On January 22, 1934, a ministerial directive asked Gutton and David to quickly undertake the study of electromagnetic detection of aircraft, with the assistance of the French Army's SEMT, Section d'Etude des Matériels de Transmission [Department of Signal Materials Studies], directed by Major Paul Labat (Figure 5).

This support proved decisive. Labat (1900-1944), who had been a schoolfellow of David at the Ecole Polytechnique, pursued a military career that had first led him to the 8th Regiment of Army Engineers at Mont Valérien (once more, in General Ferrié's team). He was known both as an excellent theoretician and as a fine experimenter. His work as head of the Section d'Etude des Matériels de Transmission made him one of the main originators of French radar [16], as will be seen on many other occasions in the course of this history.

The Electromagnetic Barrier designed by David (Figure 6) was directly inspired by the observation of the Bell engineers, and quite similar to the system tested for three years by the US Naval Research Laboratory. A shortwave



Figure 5. P. David (l) and P. Labat (r) with C. Lange from the French PTT (c), Toulon, 1941.

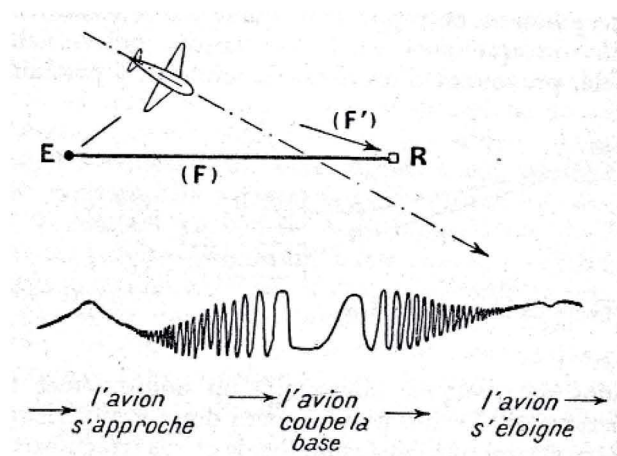


Figure 6. David's "Electromagnetic Barrier" principle [17, p. 84].

transmitter (E) and a receiver (R) were installed within reach of the limit of direct transmission. In the absence of any moving obstacle, the direct wave, attenuated only by the ground path, gave a continuous sound. However, when a plane flew over the base, a second reflected signal, shifted in frequency by the Doppler, produced an interference beating. It characterized the passage of a target. In today's terms, we would qualify this arrangement as a "continuous-wave bistatic radar."

4.1 First SEMT Experiments in 1934

The first months of 1934 were dedicated to the development of the new devices needed for the trials. In June 1934, the equipment was installed by Labat's team in a field near Le Bourget airport, which at low cost provided all the desirable "targets of opportunity." Captain Pierre Cazenave, detached by the Air Force, left a description of the experiments [18]. A first attempt, made by Camille Gutton at a 16 cm wavelength, gave no result. This could have been expected, due to a notoriously insufficient sensitivity with 0.1 W power, and due to the narrowness of the beam, which made any search impractical. However, the first sequence with a metric wave ($\lambda = 5$ m with a 50 W power), which took place on June 27, 1934, was immediately successful. When the first plane flew past, beats were clearly heard in the earphone: fast at first, then slowing down until appearing to stop when the plane crossed the transmitter-receiver line, and then accelerating again when it went away, up to distances of 7 km to 8 km for a plane flying at 5000 m.

In November 1934, a second test series was repeated. This time, signals were recorded, to set up a database and to quantify a number of beat-signal parameters, such as frequency, amplitude, time duration, and damping. The next objective was to correlate these measurements with the flight parameters: direction and speed.

4.2 Navy Tests in February 1935

From their side, the French Navy, learning about the Le Bourget results, decided to conduct their own tests by setting up an experimental barrier 19 km long between Toulon and the Giens peninsula. The frequency selected was 52.6 MHz ($\lambda = 5.7$ m). Technical assistance was provided by the LCET, Laboratoire du Centre d'Essais de Toulon [Laboratory of the Navy's Toulon Facility], and the tests took place in February 1935 in the presence of David and Gutton. The first experiment seemed to be a failure, but it was quickly explained: it was a great surprise to find that due to the specific propagation, the range over sea was two or three times the range observed over the ground. This discovery led to reducing the transmission level, or extending the base of measurement. As a result, a work plan was immediately established to look for a future barrier 200 km long, between the mainland and Corsica!

4.3 Recording Tests in July 1935

The time had come to move on to real operational tests. On April 6, 1935, the Air-DAT, Défense Antiaérienne du Territoire [Anti-Aircraft Air Defense], assigned a grant of 70,000 F (about 50,000 € today) to build three new transmitters and six receivers at the ECMR, Etablissement Central du Matériel Radio [Central Establishment of Radio Equipment]. These were to be copies of the prototypes made by David for the previous Navy experiments. Pen recorders were to be bought from Siemens. The equipment ordered had to be delivered at Section d'Etude des Matériels de Transmission by late May.

The 1935 tests were made under the control of the governmental Comité d'Etudes et d'Expériences Physiques, with the participation of three officers detached from the 401th Regiment of Anti-Aircraft Artillery. The Navy also invited delegated Captain Mouren, Chief of the Navy Scientific Research, and M. Laville, engineer and scientific collaborator at the Laboratoire du Centre d'Essais de Toulon (who was present on site from July 15 to 23) to attend the trials.

Originally planned at Metz, near the German border, the trials were finally held in the vicinity of Paris during the summer of 1935, with the assistance of the Le Bourget Air Force and the Etampes Flying School. Different places were selected to try various technical options, and to observe the influence of the ground on the optimal implementation of the transmitting/receiving bases: on the southwestern plateau (Saclay), in the southeast at Brie-Comte-Robert, and in the northeast between Le Bourget and Senlis [19]. With a total of about 30 flights of isolated planes or squadrons, more than 500 passages were recorded and calibrated:

They confirmed the possibility of detection to higher altitudes, and were used to correlate the observed

phenomena with the characteristics of the air passages, and to establish formulas giving the main flight parameters, as route and speed.

The results were very promising: excellent detections were obtained in all cases, by night or with clouded skies as well, on aircraft flying up to 8000 m at a distance of 5 km. The vertical passing was instantly known, the route direction was given to nearly 10 degrees, and the speed was determined to within 10%. The accuracy of the altitude measurement, still poor so far, seemed to be improved by a so-called *contiguous bases method*. All these parameters could be restored in less than 1 hr 30 min by a specialized team using a route calculator. From a practical point of view, the EM Barriers could be moved fairly quickly, on the existing acoustic "watching lines," or to equip new automatic watching lines at a very reasonable cost: namely, of the order of 3000 F per km. From these results, General Duchêne, General Inspector of the Défense Antiaérienne du Territoire, stated: "the Electromagnetic Detection can be seen, without undue anticipation, as the solution for the future to protect against air attacks" [20].

5. Operational Campaigns (1936-1939)

Since the arrival of Hitler to power in 1933, the international situation quickly worsened, causing the anxiety of political leaders and military staffs, particularly faced with the gravity of the air threat. In a sensational and provocative speech, Lord Baldwin had expressed his pessimistic conviction in the British Parliament: "Whatever we do, the bombers will always get through!" When General Duchêne thus concluded his report with: "The problem of an automatic aircraft detection has become crucially important: the efficiency of our defense in a future conflict depends on its solution," David could think that his studies would finally be given a high priority.

5.1 Air-DAT Maneuvers in 1936 and 1937

Things were then sufficiently established to be experimented on with a more operational basis. It was decided to evaluate the military interest in the new technology during aerial maneuvers organized every year during the summer by the Air Force. For two years, in 1936 and 1937, these tests were funded by the Comité d'Etudes et d'Expériences Physiques, and carried out by an Army detachment under the command of Major Labat and Captain Cazenave. David was called in as a reserve captain in charge of the technical direction of the trials.

In August 1936, an E-M base was merely added to a classical acoustic watching line, during the Défense Antiaérienne du Territoire maneuvers in the region of Gien (Loiret). Little is known on the progress of those 1936 trials, but Cazenave reported that 25 passages of aircraft

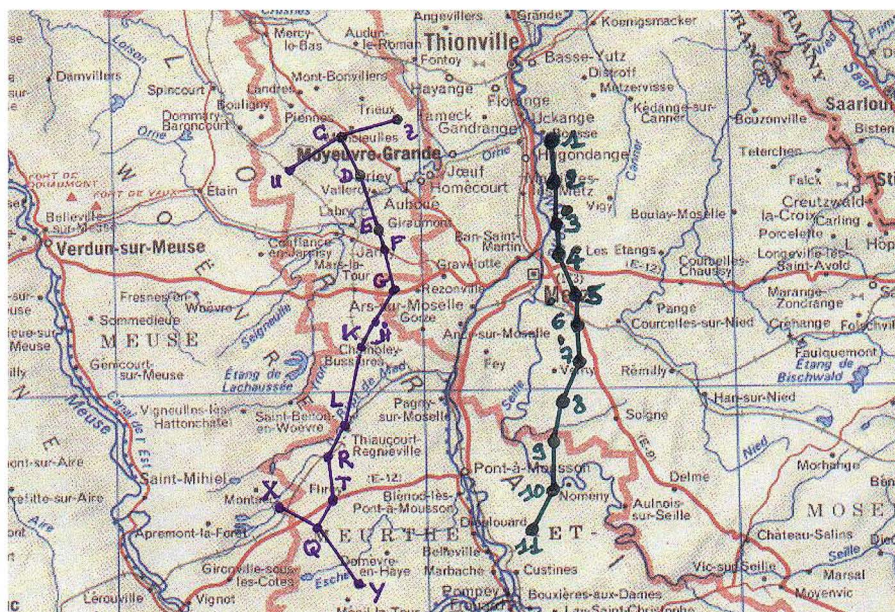


Figure 7. “Krebs” acoustic line experiments, Metz, 1936.

were detected, many of them having escaped the normal watching, and that there was no failure on the DEM side. In all cases, the measured speeds were correct, and in half the cases, the routes were also correct [18].

At the end of the year, new credits were given to the Etablissement Central du Matériel Radio to build 12 modified sets, to be used in June 1937 during the Air-Défense Antiaérienne du Territoire maneuvers in the Reims-Argonne region. With the same organization as in 1936, they were controlled by Lieutenant Nicolardot from the Air Force CEAM, Centre d’Expériences Aériennes Militaires [Center for Military Air Experiments] in Reims, with P. David still acting as a reserve Captain.

The tests took place first in June 1937 in the Reims Centre d’Expériences Aériennes Militaires. Twelve positions were established on two lines in the Argonne area, with satisfying results. According to Captain Cazenave, it was actually the first time that an exercise of fighter interception by night was achieved under DEM guidance. It also seems that a first comparison with an acoustic method was made on August 12, near Mantes. The results of six passages appeared favorable to the DEM, but this success was disputed by supporters of acoustic methods!

These acoustic methods, which should have been rendered obsolete by the arrival of the electro-magnetic detection, were still vigorously defended by most of the Air Force officers. For at least four years, their tactical use had been evaluated in two ways: the so-called “Krebs procedure” for the interception of bombers by day or in illuminated areas; and the “Idatte procedure” by dark night [21]. At the pace of maneuvers that were held only once a year, this could not speed up the matter! To further complicate

things, the evaluations were conducted by two different actors: the Centre d’Expériences Aériennes Militaires in Reims, and the CEPDCA, Commission d’Etudes Pratiques de Défense Contre Aéronefs [Commission for Air Defense Practical Studies] in Metz, both ruled by the Air Force, but not without some rivalries of competences. This was typical of a situation that created the technological backwardness of the French Army, and led to the catastrophic defeat of June 1940.

Starting on August 17, 1936, major trials of the Krebs procedure were scheduled at Metz, without DEM [21]. Eleven research stations, equipped with acoustical and optical devices, were staggered between Blettange (southeast of Thionville) and Serrières (southeast of Pont a Mousson) (Figure 7). The results were said to be satisfactory “in favorable weather,” and the report recommended setting up a permanent base around Metz to pursue the trials on more difficult situations. However, the new tests scheduled for 1937 were not ready to be included in the program of the summer maneuvers. They were delayed to September 1937, in the Reims-Laon region, still without DEM.

For its part, in 1936 the Reims Centre d’Expériences Aériennes Militaires tested the Idatte method, also without DEM. The experiments were said to have been satisfactory (32 successful interceptions on 60 passages). However, new trials in 1937 were disappointing, with poorer results: the report concluded that “there was still a long way to go!”

(To conclude this sequence of experiments, it would be worth adding that it gave David the opportunity to evaluate a new procedure that he named the “Mailles en Z.” Due to its more exploratory character, it will be detailed in Section 8).

5.2 1937-1938: A New Military Leadership

On October 20, 1937, David's barriers became a purely military matter. The leadership for the future experiments was transferred to the Reims Centre d'Expériences Aériennes Militaires, in order "to finalize its tactical use and to build up its operating procedures, in association or not with other acoustic and/or optical watching methods (Krebs, Idatte)." The collaboration of Captain David was again requested, but this time it was categorically declined by C. Gutton, Chief of the Laboratoire National de Radioélectricité. A few months later, David resigned from his position at the Laboratoire National de Radioélectricité to join the Navy as a scientific advisor. (After the war, he was attached to SHAPE to serve in a similar position, and became Chair of the French URSI Committee in 1951-1952).

As soon as November 1937, the new trials began under the command of Captain Arsac and Lieutenant Nicolardot. The objective was to select the most efficient equipment (built at Laboratoire National de Radioélectricité, Kraemer, SADIR), and to prepare the next maneuvers of 1938. From November 1937 to July 1938, the experiments followed quite continuously, in different locations close to the Army facility of Mourmelon, for instance, between La Veuve and Warmeriville (50 km), between Aguilcourt and Manre (the Suippe Valley, 60 km), and along the Marne, between Sarry and Hautvillers (45 km) (Figure 8).

Numerous tests were made by night, with planes flying with varying speeds, routes, and altitudes. In most cases, the conditions of detection were good above a floor of around 500 m. Some experiments gave rise to comparisons or associations to a Krebs procedure with acoustic devices.

In March, 1938, the international tension suddenly increased with the Nazi coup in Austria, followed by the annexation of the country to Hitler's Reich (Anschluss). It culminated in September with the Sudeten crisis and Hitler's menace to dismember Czechoslovakia, until the Munich Agreement gave a provisional and illusive appeasement.

However, the staffs were now in the logic for preparation for war. Without waiting for the maneuvers scheduled for summer 1938, Captain Arsac was asked to conclude his current tests and the DEM question. His report of July 29, 1938 [22] gave an updated inventory of his new experiments. The report concluded by suggesting some rules of operation, which seemed quite below the previous results acquired in the David period! If used alone, the DEM could only give time and point of passage, with a precision that was a function of the width of the transmitter/receiver base. It might be enhanced when the detection was achieved on two consecutive bases. However, direction and altitude measurements "remain still a goal." In the case where an electromagnetic barrier was conjugated with a conventional method such as Krebs, it was only regarded

as a complement thereto. The few advantages attributed to DEM concerned its level of automation and efficiency by night or on cloudy days.

When the tension seemed to release after Munich, a second Arsac report [23] brought some corrections to these restrictive views, saying, "The Electromagnetic method for aircraft detection should provide the Défense Antiaérienne du Territoire a new way of first order." This time, the benefits of low cost and mobility were especially emphasized. This second report concluded with recommendations for a complex system, combining three DEM lines staggered in depth to ensure the alert, the pre-contact, and the contact, in addition to an acoustic Krebs line, according a scheme experienced from June 1 to 30, 1938, at Châlons-sur-Marne (Figure 9).

5.3 Specific Developments for the Navy

During the same period, the Navy was engaged with its own needs in a self-development program, headed by M. Laville, scientific assistant at the Laboratoire du Centre d'Essais de Toulon. After the first successes in 1935, a barrier was planned to be set up between Cape Camarat (Saint Tropez) and Cap Martin (Menton), to warn of Italian air attacks on Toulon or Marseille. This program was well documented in the half-yearly reports of the Laboratoire du Centre d'Essais de Toulon [24]. It began with the study of new materials, a first step that was not without some friction between the two laboratories. The schedule of the



Figure 8. The double receiving station during an Arsac experiment at Condé, April 1938 [22].

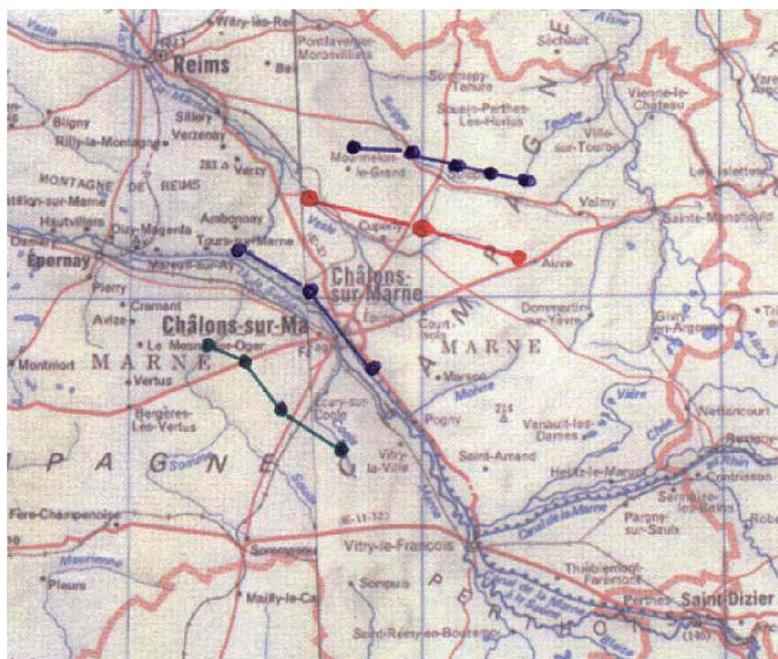


Figure 9. Triple DEM lines plus the Krebs line (in red), Châlons, June 1938.

trials themselves was impacted, delaying them until April 1936. However, after having increased the transmitter power up to 100 W, it was quickly confirmed that the specific propagation over sea provided very good detections, on bases of length from 50 km to 70 km, above a minimal altitude estimated at 400 m.

A definitive base was set up at Cap Ferrat for the transmitter and at Camarat for the receiver. It worked satisfactorily from September 1936 to April 1937 on a wavelength of 7.10 m. However, in a last test on May 26, the wavelength had to be set down to 5.75 m to take into account a summer change in the propagation. It would be seen later that this wavelength of 5.75 m was also usable in winter, and the Ferrat-Camarat equipment was finally tuned to this unique value, before being transferred to the Navy for its operational use.

(This question remained a subject of many discussions, the range of 5.5 m to 7 m normally being reserved for intercommunications between naval forces. Moreover, it was soon granted by the Cairo International Conference to TV transmissions. A note of March 30, 1938, again recommended the range 7.5 m to 10 m, and the next specifications would generally impose a wide tuning band, from 5 m to 10 m).

In June 1937, another provisional base was ordered from the Laboratoire du Centre d'Essais de Toulon, to be used in the Marseille area during the inter-army maneuvers scheduled for August. It was set up on July 27, still at 5.75 m, between Faraman and Croisette.

However, the maneuvers showed that these coastal locations did not give a sufficient warning time in case of air attacks against harbors or anchored naval forces. It seemed required to move one of the two elements of the

base offshore, onto a ship or on a buoy. A trial with the transmitter set up on a destroyer was a failure, due to the reflections on the superstructure, and the modulation caused by the roll. However, in October 1937, testing a transmitter carried on a submarine was fully successful on a base of 50 km. The submarine proved to be a very safe station, even in very bad weather. A global project was established to cover the entire coast.

A coastal network shaped as a sawtooth was studied (Figure 10), with transmitters offshore placed as far away as possible, and receivers onshore. It still remained a feasibility study to pre-define the locations, but the barrier was to be quickly deployed in the event of war, with devices easy to carry and to use.

In 1937, the ambitious project to install a barrier between Corsica and the mainland proved too costly for then. However, first conclusive experiments were done in 1938, with a transmitter embedded on the sloop-ship *Les Eparges* at 200 km off Nice, and a receiver on a van at Fort de la Tête du Chien (La Turbie)

6. The Aborted Project of a Chain Home "à la Française"

After Munich, it was no longer time to field experiments or air maneuvers, but for concrete achievements. Concerning electromagnetic detection, the Air- Défense Antiaérienne du Territoire finally took two key decisions.

The first was to acquire the means to complete a chain of about 450 km long, all along the border between the Ardennes and Switzerland. A series of thirty new devices was ordered, each including one E-62 quartz-driven transmitter (60 MHz, 300 W), and two R-62 receivers with

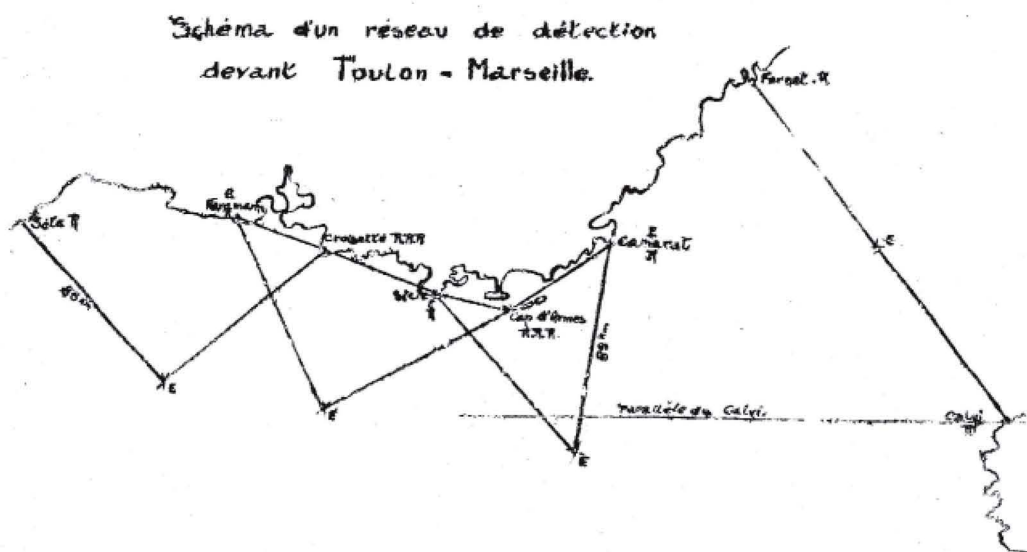


Figure 10. The coastal network project, 1938.

highly stabilized superheterodyne oscillators, alarm bells, and signal recorders. They were manufactured partly by the Etablissement Central du Matériel Radio at Issy les Moulineaux Fort, and partly by the private company La Construction Radioélectrique. They had to be delivered by spring 1939, and deployed along the borders as soon as possible.

The second decision was to create the 1st Company of Electro-Magnetic Watching, under the command of Captain Marc Contri. This would be responsible for deploying this equipment along the eastern border, in a continuous barrier operating during day and night.

However, the objective situation was not so clear! It soon appeared that this project of a Chain Home "*à la Française*" was by no means the result of any preliminary analysis, and no more the result of an implementation study, and that its architecture was absolutely improvised. Unlike the British chain, it seemed basically designed as a mobile system, which had to be deployed in a week, according to the tactical needs estimated at the moment by the Air-Défense Antiaérienne du Territoire Staff.

However, there was precisely no agreement at this level, where no fewer than three options were subject to harsh debates:

- A simple warning line, with positions spaced about 40 km on a 300 km front closest to the border. This would give only an alert (but infallible!), and a precise time of crossing the line, without direction or altitude, and even less, the number and type of aircraft.
- A line dedicated to fighter guidance, 60 km long with stations spaced at 10 km, between Laon and Hautvilliers, to stop air attacks that would have violated Luxembourg and would go to Paris.

- (As an emergency option, which became more pressing when the war situation deteriorated) moving this line around Paris.

In the same way, the creation of the company was nothing but the regularization of a situation that already pre-existed at the Centre d'Expériences Aériennes Militaires, where a team had been gradually constituted to ensure David's barriers tests. It was thus decided to set up the E-M Company from this first Electro-Magnetic Detection Section in Reims, with a staff reduced to 45 people, nine cars and... three bikes! Its basic mission was to insure the Centre d'Expériences Aériennes Militaires experiments, while providing training for the future managers of a maneuver unit that could be deployed in case of conflict. However, there was an advantage: it was prescribed that this detachment should not in any way be dispersed at the mobilization.

The height of the confusion came when some clear-sighted officers, aware of the imminent threat, advocated an urgent solution based on Anglo-French cooperation. Major Labat, head of the Section d'Etude des Matériels de Transmission, met Robert Watson-Watt on several occasions. Labat invited Watson-Watt to visit Labat's own laboratories at the Fort of Issy Les Moulineaux, where he was building up the equipment of David. Even if Watson-Watt was very skeptical at this time, the British position changed after March 1939, when they considered a possible extension of the Chain Home protection towards the German borders. They also had to ensure air coverage for the British Expeditionary Force, which would be concentrated in the region of Lille. In April 1939, a French mission, led by Lieutenant Ballande, was invited to visit British laboratories and test facilities. Ballande came back fully subdued: "The information that was given stunned us" [25]. On his return on April 19, he quickly established a project to meet the most urgent needs, with thirteen fixed-station type CH and

nearly forty mobile station GL Mark I, for a total amount of 440 million F. The order was passed as soon as April 25. If we consider that during the previous years the bulk of the Défense Antiaérienne du Territoire annual funding was given to the purchase of sound-locating devices, and DEM was taken into account only as an extra, “provided it remained reasonably cheap!” it is clear that this order signed the death warrant of the French DEM.

The first stations were to be installed using British equipment and French-made infrastructure, energy supplies, and antennae. A few days after war was declared, Britain sent their specialists to draw up the plans for a chain of thirteen CH stations, which were to be supplied in September 1940. However, the war’s circumstances dictated otherwise.

One can understand that the deployment of the 1st Company of Electro-Magnetic Detection remained discreet. In spring 1939, it had received the Etablissement Central du Matériel Radio materials, which had to be used to build the “French Electromagnetic Barrier” along the eastern border. Military archives have preserved some staffing tables, showing that the company included at the time about 200 soldiers and 10 officers. However, we know very little about their occupations during the first months of the so-called “phony war.” According to Cazenave [18],

the 1st Company of DEM set up a continuous barrage from the Belgian border to the Alps, which worked remarkably in 1939-1940, and fully met the expectations

expressed in the early 1936. The number of failures was extremely limited, and virtually any group of aircraft or isolated aircraft crossing the barrier was detected.

However, nothing is known about the sites of implantation, probably modeled on the pre-existing air-watching lines of the Défense Antiaérienne du Territoire. One can especially ask where the alerts were transmitted, and how they were used.

Ironically, the equipment proved its advantage of mobility, especially during the debacle of June 1940. Clearly, the orders to retreat and to destroy stations given by General Vuillemin, Chief Commander of the Air Force, tried only to follow a situation that escaped him. One example was when Captain Contri was ordered on June 8, 1940, to set up a new barrier on the Swiss border [26]!

Paris was occupied on June 14, 1940, and the armistice, signed three days later, dismantled France into two parts. Contri and his company were lucky to have found themselves on the right side of the Demarcation Line, in the so-called Free Zone. Their journey ended at Cavaillon in Provence, where Contri was given the final order to deploy his equipment on the air-watching line “Y,” north of Marseille.

The company, which still numbered about one hundred men, had saved eight E-62 transmitters and five double R-62 receivers from the debacle. They were deployed as

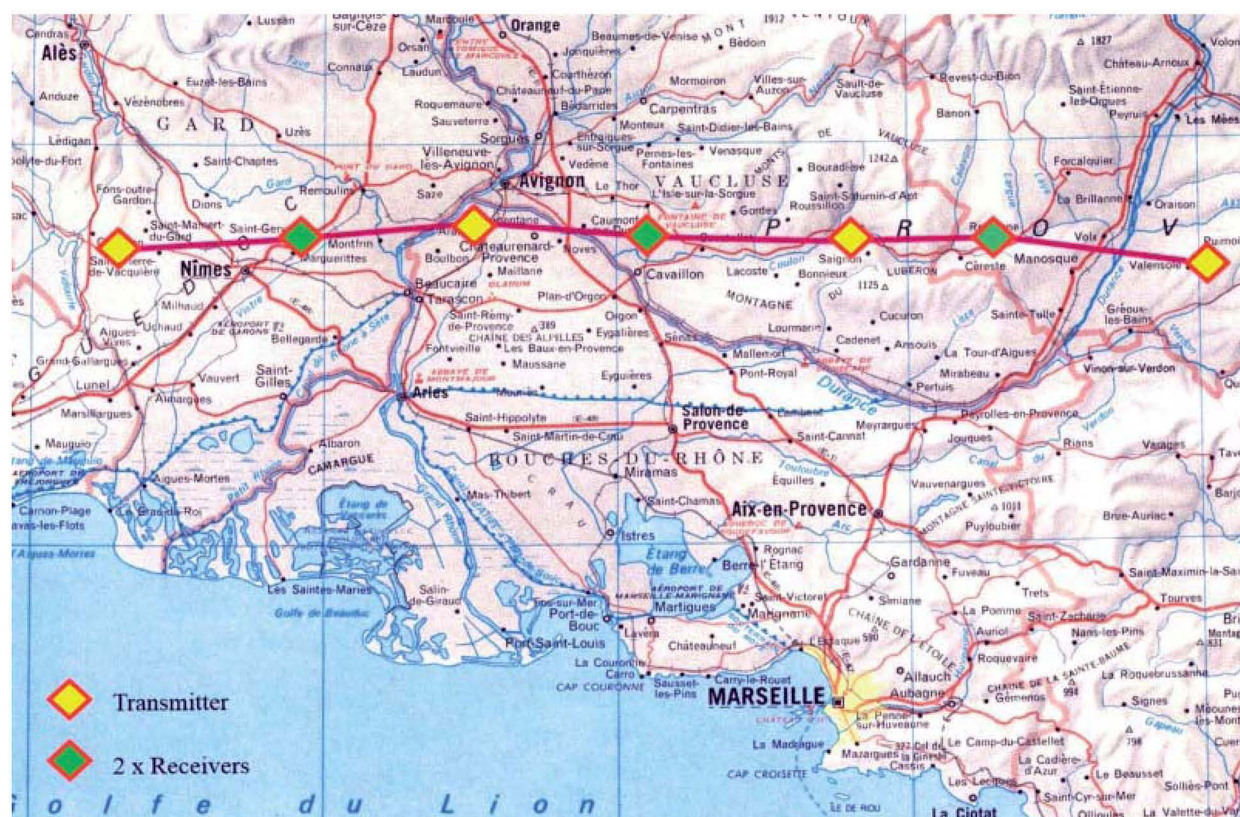


Figure 11. The last David's barrier at Valensole, 1940.

a last EM Barrier from Montperat (Gard) to Valensole (Vaucluse), with intermediate positions at St. Gervazy (Gard), Barbentane, Velorgues {Vaucluse}, Apt (Vaucluse), and Reillanne (Basses-Alpes) [18, 27] (Figure 11).

The installations, which had not much more to hide, were inspected on March 24, 1941, by the 5th Joint Commission for Armistice Control, accompanied by two German engineers, who questioned the French operators mainly about English radars [28]. The EM Barrier remained authorized in so far as it was only a warning device, but should never be used for fighter guidance. This situation lasted at least until the invasion of the southern Free Zone by German troops on November 11, 1942.

6.1 The Navy EM Barriers

From the Navy side, things were more advanced when the war broke out. Unlike the Air Force, the Navy already had an operational network of EM Barriers on the Mediterranean coast, from the Camargue west to Ramatuelle east, covering all military or industrial areas around Marseille and Toulon. If we refer to the project of Figure 10, four onshore barriers were now in operation, and four with a transmitter offshore (with the exception of barrier No. 6) were ready for operation [29].

The devices were sheltered in wooden huts (Figure 12) giving the operators the best conditions to ensure the watch. Two types of materials from different origins were used:



Figure 12. A wooden hut for a Navy EM detection post, 1940.

- Laboratoire du Centre d'Essais de Toulon devices (transmitter 100 W, modulation 600 Hz, super-reactive receiver, bandwidth limited to the range 5.5 m to 5.8 m, detection by earphone only)
- Thomson-SADIR devices (transmitter 50-75 W, modulation 600-800-1000 Hz, superheterodyne receiver), tunable in the range 7.5 m to 10 m, dual recorder Brion-Leroux.

Other methods were also explored. The Navy did not follow the Air Force politics of purchasing English radars, but chose to pursue its own research, using only the English experience as an inspirational source. By late 1938, a crash program was launched, calling on the participation of all French companies, large and small, operating in the field of radio engineering. They were asked to divert any equipment currently under manufacture for other purposes to the new DEM projects. The most significant achievement was made by LMT Laboratories, which diverted a powerful transmitter with completely unusual specifications for the time (30 kW at 46 MHz), intended for the Eiffel Tower TV station. It was made to work in a pulse regime ($P_p = 350$ kW at 48.5 MHz), to be used as an early warning radar, very much more ambitious than any other previous French project. It was installed in February 1940 on the island of Port-Cros, off Toulon [30].

Unfortunately, this equipment, which had been said to be “remarkable for its time,” had a sadly short operational life: one week! It worked well after the declaration of war by Italy on June 10, 1940. During the night of June 12, it detected an attack by Italian planes over Toulon, giving an early warning at 120 km that led to 38 Italian planes being shot down. However, after France asked for armistice on June 17, 1940, the Navy decided to dismantle the station, which remained hidden on the island in separate elements.

On the other hand, the Navy Barriers of the 3rd Region, like the Air Barrier of Valensole, were maintained in operation, with the agreement of the 5th Joint Commission for Armistice Control, until the whole French fleet was scuttled to escape German capture in November 28, 1942.

On the Atlantic coast, David was asked to plan a full program of EM Barriers to protect the naval base of Brest. Six barriers were planned, according to Figure 13.

In August 1939, two barriers were operating (Ouessant (T): Pointe du Raz (R); Ouessant (T): Ile Vierge (R)). Three others were under construction (Ploumanach (T): Ile Vierge (R); Penmarc'h (T): Pointe du Raz (R); Penmarc'h (T): Belle-Île (R)) [31]. Transmitting and receiving devices worked in a wavelength range from 4 m to 10 m. They were made at the Brest Arsenal, for a total cost of 40,000 F.

All these barriers, operational or under construction, were destroyed at the arrival of German troops in Brittany on June 20, 1940.

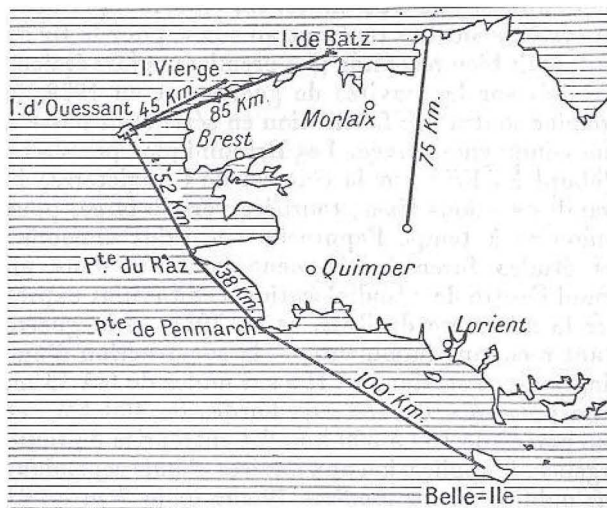


Figure 13. EM Barriers around Brest, 1940 [17].

7. Other Developments: Britain and Japan

In Great Britain, phenomena similar to the NRL observations were published on June 3, 1932, in a Post Office report [32], with an explicit chapter dealing with “interferences from Aeroplanes.” However, no attempt was made to apply the beat method as a substitute to the giant acoustic mirrors, which were tested at this time before the Chain Home deployment.

In his autobiographical book [33], Sir Robert Watson-Watt, claiming for himself the title of “Father of Radar,” refused to consider those interference methods – and the bistatic systems of Taylor or David, as well – as “true radar.” It is thus a bit funny to note that he used the same principle when he hastily organized his famous Daventry experiment on February 26, 1935, to prove the feasibility of the radio-detection method that he had proposed in his memorandum dated February 14.

Under the supervision of the Tizard “Committee for the Scientific Survey of Air Defence,” represented by its secretary, Arthur P. Rowe, Watson-Watt settled receiving equipment at $\lambda = 49$ m in a van parked in a field some kilometers from the Daventry BBC radio station. He asked a Heyford bomber to fly into the radio beam (Figure 14). The interference that appeared when the plane was at an estimated distance of about eight miles was significant enough to definitively convince A. P. Rowe that an aircraft would reflect enough energy to detect its presence [35]. As it is known, the following decisions were not long to come!

However, it was in Japan, during the first years of the war with China (1937-1945), that the *beat method* found its most significant operational application. At the beginning, Masatsugu Kobayashi, a TV engineer at NEC, followed the same path as his American, British, or French

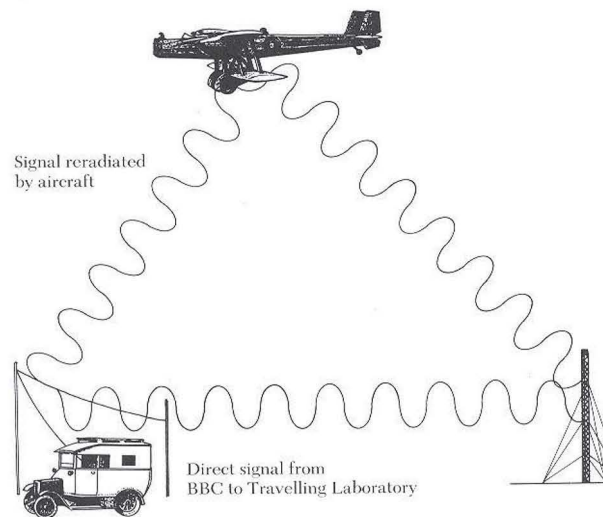


Figure 14. The Daventry experiment [34, p. 71].

predecessors, but this time it resulted in a true military use. In May 1938, when making preliminary tests for the TV transmission of the Olympic Games that were to be held in Tokyo in 1940, he noticed blurring in his pictures, which was strongly correlated with aircraft takeoffs or landings at the nearby military airport of Tachikawa. The Olympic Games were cancelled after the outbreak of the conflict with China, but the observation was reported to Captain Kinji Satake at the Army’s Scientific Research Laboratory. Satake found interest and funds to create a study group, including representatives from Tokyo Electric Company, JRC (Japan Radio Company), the Osaka and Tokyo Imperial Universities, and, of course, NEC, under the leadership of Kobayashi.

The team developed a system quite similar to David’s Electromagnetic Barrier, in the 40 MHz to 60 MHz frequency range, with distances between transmitters and receivers of up to 100 km. As soon as it was engaged against China, the Japanese Army adopted this radio detector, designated as a Radio Locator Type A, or Bistatic Doppler Interference Detector (due to the sound generated by the beats, it was also known as the “Bow Wow type” or “*Wan Wan Shiki*”). It proved to be of value in China, detecting targets at more than 300 km distance [36]. It was said to have been built by NEC and Toshiba from 1941, in several hundred copies, in different versions.

8. The “Mailles en Z” (Z Lattices) Method, A Generalized Multi-Static Sensor System for Three-Dimensional Localization

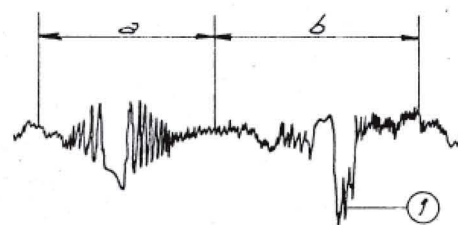
As a matter of fact, it was pretty clear that the Electromagnetic Barriers had failed to fulfill the two functions for which they had been intended, although the reasons were not only technical. Faced with obsolete

acoustic devices, they had not managed to create a decisive advantage as guidance systems for fighters in the dark night. More especially, the lack of a precise estimation of the altitude of planes made them unacceptable for anti-aircraft fire control. In those pre-war times, this was mainly due to the ignorance of modern signal-processing tools (i.e., methods for solving inverse problems, and the maximum-likelihood estimator), which would today put the matter within the scope of a PhD student! At the Reims Centre d'Expériences Aériennes Militaires, the military operators, more often without real technical competence, could only wonder about the complex shapes appearing on their recorders when the situation was a bit complicated, as in Figure 15 with an over-flight of three aircraft. Unavoidably, there were some right-thinkers who said that “staying at lookout in the darkness of a tent facing an oscilloscope was not a military attitude!”

To extract the desired parameters, the operator could only rely on charts empirically established after a number of field experiments, with a rather doubtful reliability (Figure 16) !

To give a final answer to the question of altitude measurement, in 1937 David proposed an improved configuration by arranging transmitting and receiving stations on two parallel lines, separated by a few kilometers, according to a design he called “Mailles en Z” (Z lattices) [37] (Figure 17). A new credit of 60,000 F enabled him to build a pre-series of 12 new sets at the Fort d'Issy, designed to experiment with this new method. During the preparatory tests before the maneuvers of the summer of 1937, he obtained from the multiple combinations of transmitter-receiver lines a target-speed accuracy of close to 10%, the direction $\pm 20^\circ$, and the altitude ± 500 m.

However, this method was considered too complicated to manage without any processing machine at that time. Cazenave, who attended the trials, acknowledged that the lack of interest shown by the Défense Antiaérienne du



Passage de : a) 3 mureaux bien groupés
b) 1 mureaux

Figure 15. A recording of a passage of four planes, 1936 [22].

Territoire for the data coming from a single line was not stimulating to acceptance of an over-cost for its doubling, especially as hopes then focused on the adoption of the English RDF system. From October 1937 (as it was said above), David was left out of all new developments of Air Barriers. Despite the support of Major Labat, this new configuration – by all means the most innovative, as the first historical approach of a true multi-static system, and undoubtedly of real efficiency – was not experimented with in the following 1938 campaign.

9. Epilogue

When WWII started, certain things seemed understood: the pulse radar system prevailed everywhere. Watson-Watt “theorized” this restrictive point of view in the chapter “What is Radar” of his memoirs [32]. David himself endorsed this new trend when in October 1938 he concluded a memorandum to the Committee of Physics and Experiments with a strong recommendation to follow the new way of monostatic pulse systems [38]. During the war, apart from the Japanese “Wan Wan Siki,” the most

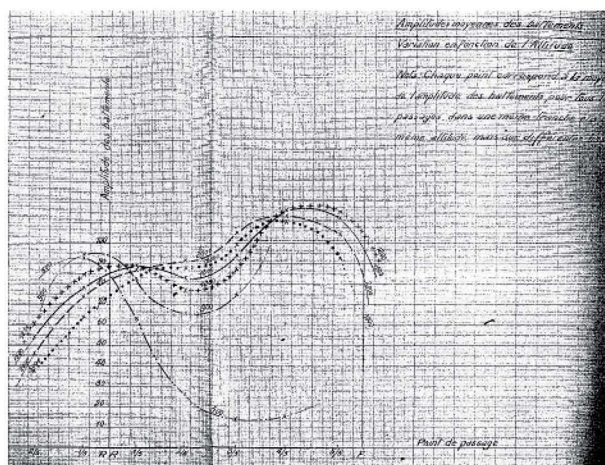


Figure 16a. Charts for the evaluation of flight parameters: the passing point [23].

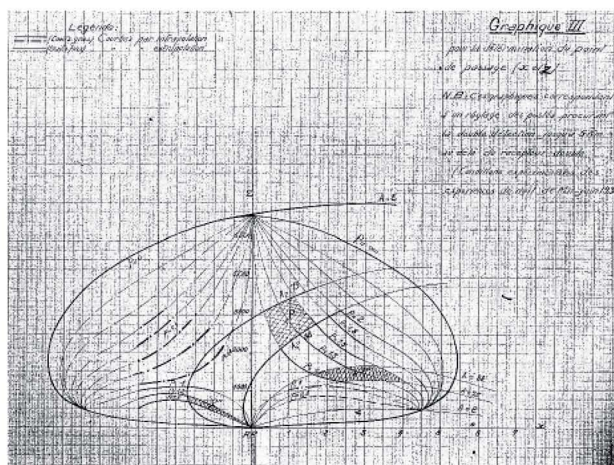


Figure 16b. Charts for the evaluation of flight parameters: altitude [23].

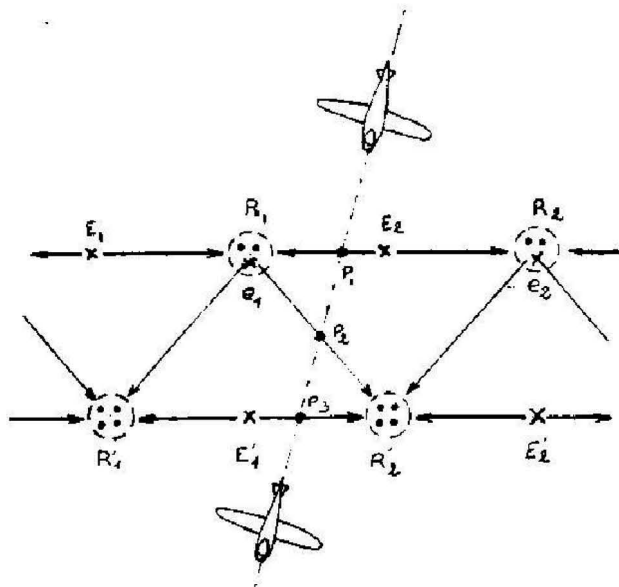


Figure 17. David barriers: the “Mailles en Z” configuration, June 1937 [37].

interesting innovation came from the German side. This was the imaginative “Klein Heidelberg,” which used as non-cooperative transmitters the English stations of the Chain Home, themselves [39]! After the advent of the magnetron in 1942, leading to the exclusive use of centimeter wavelengths, the architecture of “classical radar” seemed fixed for a long time. During two or three decades, progress could be summed up into “how to focus more and more peak power into shorter and shorter pulses and thinner and thinner beams.” This led to the giant air surveillance radars of the 1970s, impressive electromechanical monsters pushed to the latest technological limits, until they finally appeared as not totally free from any drawback: to avoid ambiguities when range and speed measurements had to

be combined, for instance, or when a target pursuit needed increased beam agility.

This was the time when CW radars found new interest, and appeared as an alternative technique that was only dormant. The “bistatic radar” was introduced as a fully separate topic in the second edition (1990) of Skolnik’s *Radar Handbook* (Chapter 25, by N. J. Willis) [40]. However, according to Willis, the name itself had been coined as early as 1952 by Siegel and Mahol [41]. The subject was updated in 2007 by Willis and Griffiths [42]. Many examples were quoted in these books. We can add in France the new “HF Fences” developed by LCTAR in the 1980s, and the bistatic GRAVES by ONERA for satellite tracking [43]. However, at that time the matter did not stop at a simple CW line between two points. It benefited from the advent of distributed or sparse array theory, of which the French RIAS [44], and its Chinese copy [45], were two early precursors.

Today, all these systems are gathered under the banner of “MIMO (multi-input multi-output) radars” [47] (Figure 18), which covers an infinite variety of multi-static configurations. The modern theories of space-time signal processing, and the capabilities of digital computers – the two elements that David lacked for his “Mailles en Z” – have opened the way to free the imagination of a new generation of radar designers.

10. Acknowledgments

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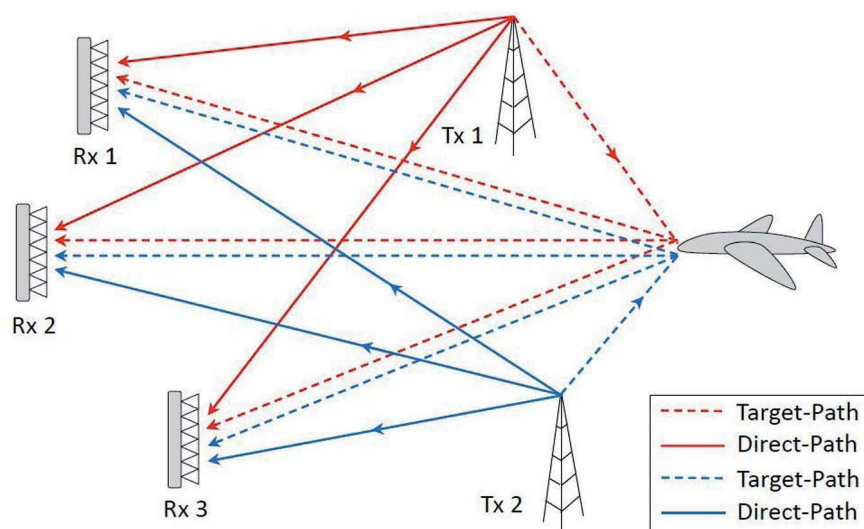


Figure 18. An example of a modern MIMO radar (from Himed [46]).

11. References

1. G. Galati, *100 Years of Radar*, Berlin, Springer International Publishing AG, 2015.
2. R. C. Watson, Jr., *Radar Origins Worldwide*, Bloomington, Trafford Publishing, 2009.
3. Y. Blanchard, *Le Radar, 1904/2004: Histoire d'un Siècle d'Innovations Techniques et Opérationnelles* [The Radar, 1904/2004: One Century of Technical and Operational Innovations], Paris, Ellipses ed., 2004 (in French).
4. Y. Blanchard, "The Origins and Development of Radar: An Account of the French Contribution," in *100 Years of Radar*, DGON (Deutsche Gesellschaft für Ortung und Navigation), 2005, pp. 91-120.
5. H. E. Guerlac, *Radar in WW II*, New York, Thomas Publishers, 1987, pp. 211-213.
6. Y. Blanchard, "Maurice Ponte and Henri Gutton, Pioneers of Early French Studies on Resonant Magnetron, 1932-1940," Proceedings of IET International Cavity Magnetron Conference (CAVMAG 2010), Bournemouth, April 19-20, 2010, pp. 5-10.
7. Y. Blanchard, G. Galati, and P. van Genderen, "The Cavity Magnetron: Not Just a British Invention," *IEEE Antennas and Propagation Magazine*, **55**, 5, October 2013.
8. R. Mesny, "Les Ondes Très Courtes" [The Very Short Waves], *L'Onde Electrique*, **2**, 25, January 1924, pp. 25-37; **2**, 26, February 1924, pp. 99-110.
9. Capitaine Jund, Lieutenant-Colonel Laure, and P. David, *Procès-Verbal des Essais d'Ecoutes de Bruits Rayonnés au Palivestre* [Minutes of Listening Tests of Radiated Noise at Palivestre], Commission d'Expériences de Bourges, April 15, 1930.
10. P. David, "Historique de la Détection Electromagnétique" [History of Electromagnetic Detection], typed report, 1938, with a handwritten note by David: "copy of a 1938 report destroyed in 1940 as all the mentioned references."
11. P. David, "Memorandum on Aircraft Detection," pli SOLEAU n°4944N, French Industrial Property, May 5, 1930; "Opening Minute of n°4944N," May 1935.
12. General Challéat, "Letter to General Commander of French Signal Corps," n°340 S/E, February 20, 1939.
13. R. M. Page, *The Origin of Radar*, New York, Anchor Books, Doubleday and Co, 1962.
14. A. H. Taylor, L. C. Young, and L. A. Hyland, "System for Detecting Objects by Radio," US Patent No. 1981884, filed June 13, 1933.
15. C. R. Englund, A. B. Crawford, and W. M. Mumford, "Some Results of a Study of Ultra-Short-Wave Transmission Phenomena, Field Fluctuations from Moving Bodies," *Proceedings IRE*, **21**, March 1933, pp. 475-493.
16. P. Revirieux, "Paul Labat et la Détection Electromagnétique" [P. Labat and the Electromagnetic Detection], *La Liaison des Transmissions*, n° 59, September-October 1969, pp. 10-13.
17. Pierre David, *Le Radar*, coll. Que Sais-Je ?, Paris, PUF ed., 1969.
18. Colonel Cazenave, "La Détection Electromagnétique en France avant le Radar" [Electromagnetic Detection in France before Radar], *Bulletin de Liaison de l'Amicale des Transmissions de l'Armée de l'Air*, February 1970, pp. 18-19.
19. Pierre David, Letter to Pierre Cazenave, April 20, 1968, Cazenave's personal archives.
20. General Duchêne, "Détection des Avions en Vol" [Flying Planes Detection], correspondence to Air Ministry, n° 5.791/S, March 28, 1936, SHAT (archives of French Army Historical Service), Vincennes.
21. CEAM, Centre d'Expériences Aériennes Militaires [Center for Military Aerial Experiments], "Rapports Secrets sur les Expérimentations de Chasse de Nuit, 1936-1938" [Secret Report on Night Fighting Tests, 1936-1938], file 7 N 3946, SHAT (Archives of French Army Historical Service), Vincennes.
22. Capitaine Arsac, "Résultats Obtenus avec les Matériels de Détection Electromagnétique à la date du 5 juillet 1938" [Review of Electromagnetic Detection Results on July 5, 1938], CEAM report n° 1057/S, July 29, 1938, SHAT (Archives of French Army Historical Service), Vincennes.
23. Capitaine Arsac, "Valeur du procédé électromagnétique de détection des avions: précision, délais d'utilisation, application à la manœuvre de chasse" [Value of planes Electromagnetic Detection, precision, reactivity, application to fighter guidance], CEAM report n° 1376/S, 10th October 1938, SHAT (archives of French Army Historical Service), Vincennes.
24. LCET, "Comptes-rendus semestriels" [Half-year reports], Centre d'Etudes de Toulon, nos 82 (August 1, 1936) to 88 (August 1, 1938).
25. H. Ballande, *De l'Amirauté à Bikini*, Paris, Presses de la Cité, 1972 (the copy we used was widely commented by margin notes handwritten by Col. Cazenave).
26. Général Vuillemin, "Organisation d'un Barrage de DEM. sur la Frontière Suisse" [Setting up a E-M Barrier on the Swiss border], letter n° 706bis/I.G.D.Aé/3/S, to the Signal Commander of DAT, June 8, 1940).
27. Colonel Sezestre, "La Compagnie de DEM, 1940-1944," typed note to Col. Cazenave, 1969, Cazenave's personal archives.
28. Contre-Amiral Aubin, "Activité de la Commission n°5, Détection Electro-Magnétique," [5th Commission Activities, E-M Detection], letter n° 721 EM ARM, to Navy's Chief Admiral, April 9, 1941.

29. Contre-Amiral Michelier, "Situation de la DEM en 3^{ème} Région au 15 Octobre 1939, [Situation of E-M Detection in 3th Region at October 15, 1939], letter n° 578 EMG Trans, to Maritime Prefecture of Toulon (October 20, 1939).
30. Ernest Giboin, "L'évolution de la Détection Electromagnétique dans la Marine Nationale" [An history of the E-M Detection in the French Navy], *L'Onde Electrique* n°287, February 1951, pp. 53-64.
31. Contre-Amiral Tavera, "Etablissement de barrages électromagnétiques en 2^{ème} et 5^{ème} Région" [Setting up E-M barriers in 2nd and 5th Regions], note n° 1467 E.M.G.1 "Secret" aux Préfets maritimes des 2^{ème} et 5^{ème} Régions maritimes (August 4, 1939).
32. Nancarrow, Mumford, Carter, and Mitchell, "The Further Development of Transmitting and Receiving Apparatus, Part V: Interference from Aeroplanes," British Post Office Radio Report n° 233, London, June 3, 1932.
33. Sir R. Watson-Watt, *Three Steps to Victory, A Personal Account by Radar's Greatest Pioneer*, London, Odhams Press, 1957.
34. B. Johnson, *The Secret War*, London (BBC ed.), 1978, p. 71.
35. A. P. Rowe, *One Story of Radar*, Cambridge, Cambridge University Press, 1948, p. 8.
36. Y. Nakagawa, *Japanese Radar and Related Weapons of World War II*, Laguna Hills, CA, Aegean Park Press, 1997, pp. 15-16.
37. P. David, "Quelques Commentaires sur l'Histoire du Radar" [Some Comments about the Radar Story], *La Liaison des Transmissions*, n°75 (May-June 1972), pp. 15-20.
38. P. David, "Note au Comité d'Etudes et d'Expériences Physiques" [Note to CEEP, Committee for Studies and Physical Experiments], October 1938.
39. H. Griffiths, "Klein Heidelberg, the First Modern Bistatic Radar System," *IEEE Transactions on AES*, **46**, 4, October 2010, pp. 1571-1588.
40. N. J. Willis, "Bistatic Radar," in M. L. Skolnik (ed.), *Radar Handbook, Second Edition*, New York, McGraw-Hill, 1990, Chapter 25.
41. K. M. Siegel, "Bistatic Radars and Forward Scattering," Proceedings of the National Conference on Aeronautical Electronics, May 12-14, 1958, pp. 286-290.
42. N. J. Willis and H. D. Griffiths, *Advances in Bistatic Radar*, Raleigh, NC, SciTech Publishing, 2007.
43. T. Michal, J. Bouchard, and J.-P. Eglizeaud, "GRAVES: The New French System for Space Surveillance," Proceedings of the 4th European Conference on Space Debris (ESA SP-587), Darmstadt, April 18-20, 2005, p. 61.
44. J. Dorey, Y. Blanchard, and F. Christophe, "Le Projet RIAS, une Approche Nouvelle du Radar de Surveillance Aérienne" [RIAS Project, a New Approach of Air Sur-

veillance Radars], *L'Onde Electrique*, 64, 4, July-August 1984, pp.15-20.

45. C. Baixiao, Z. Shouhong, W. Yajun, and W. Jun, "Analysis and Experimental Results on Sparse-Array Synthetic Impulse and Aperture Radar," Proceedings of IEEE International Radar Conference RADAR 2001, Beijing, 2001, pp. 76-80.
46. B. Himed, D. E. Hack, and L. K. Patton, "Direct Cartesian Localization in Passive MIMO Radar Networks," Proceedings of IEEE International Radar Conference RADAR 2014, Lille, October 13-17, 2014, WEO.2.5.
47. Eli Brookner, "MIMO Radar Demystified," *Microwave Journal*, **56**, 1, January 2013, pp. 22-44.

Introducing the Author

Yves Blanchard was born in 1942. He is a consulting engineer. He graduated from ISEN Lille in 1966. He has been a research engineer in sonar and radar for 25 years. He was first with the French National Centre for Aerospace Studies & Research (ONERA), where he worked as project manager on innovative radars such as the HF radar "RIAS" and the OTHR "Nostradamus." He then joined industry at Thomson-CSF (now Thales), as Research Director at Thomson Sintra Underwater Activities, and at Thomson-CSF Missile Electronics. He ended his career as Technical Director of the Missile Electronic unit of Thales Airborne Systems.

He is also a well-known researcher into the history of radar, and has given nearly 40 papers and conferences on the subject. He is the author of a general history of radar developments, acknowledged in France as a reference book: *Le Radar 1904-2004, Histoire d'un Siècle d'Innovations Techniques et Opérationnelles* (Ellipses ed., Paris, 2004). He is currently working on the French radar story before WWII, and on the German radars used in occupied France during the war. He is Chair of the Association for the Development of the German-French Museum of Radar at Douvres la Delivrande, Normandy.

